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Contribution on non-hydrodynamic lubrication.

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First Communication

Synopsis: Non-hydrodymanic lubrication is first defined; then the theoretical principles of the phenomena relevant in this connection are touched upon. An instrument of large resolving power and very high accuracy and reproducibility in determinations of the coefficients of friction is described. With the aid of this instrument preliminary light is thrown on the most important factors to be taken into account in investigations of this kind.

Index

I. Definition of non-hydrodynamic lubrication. General Remarks on the process of lubrication.

The term non-hydrodynamic lubrication has been chosen for that region of which the laws are not yet known. Hydrodynamic effects which are obscure or indeterminate, properties of films of molecular thickness at boundary surfaces, chemical reactions in the lubrication boundary layer, etc. all belong here. The proposed terms (I) of "boundary" or "epilamen" lubrication and strictly speaking also mixed or partial lubrication 1.), in which further subdivisions are conceivable, are only of theoretical interest as long as their properties have not been definitely ascertained, as they cannot be exactly determined or characterised by experiment. One definite case of boundary lubrication would be when two absolutely atomically flat surfaces lie on each other and may be displaced parallel to each other are separated by a known number of molecular layers of lubricant. The question of how long these surfaces would remain atomically flat when they glide along each other would still remain open.

An attempt was made to observe the lubrication process as a function of various factors with the aid of a peculiarly simple and very sensitive apparatus. The nature of the point of lubrication that was chosen (three balls as a guiding bearing, one ball as a sliding body) necessarily entails simultaneous working in the regions of various lubrication phases (e.g., the known hydrodynamic phase 2.)) particularly when the balls are still undamaged. Only those lubrication processes, however, which offer a high resistance to sliding have a predominant effect in practice; only the effective load differs in each case. This also applies more or less to other forms of test-apparatus, conditioned as it is by the roughness of the surface itself.

The integrated values obtained therefore, to a varying extent, cover discrete frictional states of high frictional resistance.

It is therefore not the purpose of this communication to add one more to the large number of available instruments and, corresponding to its specific characteristics, to cultivate discrete lubrication or frictional states, deformation resistances, etc. to a greater or smaller degree of reproducibility, and from this directly to deduce general connections between the instrument and lubrication in practice, as has been done so often.

Before discussing the individual results here are the general principles for a consideration of the relevant problems and experimental results.

Wear was immediately observed in all the measurements taken with the instrument. Now it is to be supposed that under constant external conditions this wear will lead to a point when, depending on the type of lubricant, the surface will have acquired a quite definite basic structure. It is known that every surface of a solid or liquid material possesses a definite surface tension which is due to the fact that the surface molecules or atoms are only partially capable of neutralising the forces that keep them together. If a second substance is brought into the neighbourhood of the first, the residual forces become more or less bound and the surface-tension or energy falls.

The total surface or interfacial energy of a substance is given by:

$$U = \sigma\omega - T\frac{d\sigma}{dT}\omega$$

where σ is the surface or interfacial tension
ω is the interfacial energy
$\sigma\omega$ is the free interfacial energy
$T\frac{d\sigma}{dT}\omega$ is the bound energy (latent surface or interfacial energy).

The surface or interfacial energy must be found by experiment.

Dupré (II) established the following expression for the work obtainable when two liquids are brought into contact:

$$A = \sigma_a + \sigma_e - \sigma_{ae} \qquad (2)$$

Where σ_a and σ_e are the surface tensions of the liquids and σ_{ae} is the interfacial tension at the point of contact itself. If one tries to apply this expression directly to the wear 3.) then σ_a and σ_e ($\sigma_a = \sigma_e$) denote the interfacial tension between working material and lubricant and σ_{ae} the interfacial tension in the material of the point of lubrication; this is equal to zero. Therefore 4.)

$$A = 2\sigma \qquad (3)$$

The mechanical work per cm^2 which has to be expended in detaching particles from the point of lubrication would therefore be twice the interfacial tension between the point of lubrication and the lubricant i.e. a function of this quantity.

The force with which a surface tends to reduce its area corresponds to the surface or interfacial tension. In (crystalline) solid bodies, as opposed to liquids, this tension differs micro-locally, depending on the distribution of areas, edges and corners in the (microcrystalline) surface structure. The surface molecules or atoms are subjected to a unidirectional pull.

Depending on the lowering of the interfacial tension due to the presence of a neighbouring medium this pull is modified, particularly at edges and corners. The molecules, atoms or smallest particles will (depending on the neighbouring phase) vary in the ease with which they may be transferred, particularly at the points mentioned, from the original zone into the neighbouring one.

W.O.Engelhardt (III) showed that the mechanical work necessary to grind different substances to a given extent (e.g. quartz with carborundum powder) varies for the same grinding material when the liquid used is varied. He relates the volume ground-off to the interfacial energy of the grinding material with respect to the liquid in question, assuming that the substance is ground down to a "constant degree of fineness". The increase in surface area (ground-off volume) would be inversely proportional to the interfacial energy (in agreement with the hypothetical equation (3)). This paper gives original quantitative data on cutting hardness as a function of the liquid used. Whether the state of subdivision of the grindings (Abschliff) remains constant is however open to question. After what has been said above it is quite plausible that the resulting "hardness" of the cutting body might possibly be due to a different form of abrasion (size and kind of the torn out particles (IV)). This would result in the above mentioned dependence of the surface structure of the sliding surface on the lubricant. The grindings produced, varying both quantitatively and qualitatively, may react with the oxygen dissolved in the oil or any other chemically active substances and thus yield new substances. Friction and wear loss are bound up with these processes.

The following properties of very thin films are of interest in this connection and may be recalled here: if measuring blocks (highly polished plane surfaces) to which a trace of liquid has been applied, are brought into contact they can only be separated by force. The cause of this phenomenon is not yet quite clear. As a primary factor the following has been discussed (V): the lubricant molecules cover the two surfaces and orientate themselves according to the fixed lattice points of the atomic lattices of the two metals. The mechanical work, per cm^2, which must be expended in order to separate them from the boundary face is again given by equation (2) where σ_a now denotes the surface energy at the point of lubrication, σ_e that of the lubricant, σ_{ae} the interfacial tension between point of lubrication : lubricant (VI).

The equation (2) (and (3)) is useful in practice only under certain conditions, because the interfacial tension of solid bodies can be estimated only approximately at the present time, just like the interfacial tension of very thin (molecular) films between two solid boundary faces. From measurements of interfacial tension of mercury and of contact angles values are obtained which make it apparent that the adhesive strength of molecules adsorbed at solid boundary faces should be similar to the cohesive strength of a solid substance. Lubricant molecules cohere about equally strongly; the tensile strength of liquids (VII) is therefore the same order of magnitude as that of solid bodies. This tensile strength becomes effective when the molecules of the liquid cannot be displaced relative to one another but are actually separated; this is the case, more or less, when tensile stresses come into play very rapidly or when the mobility of the liquid molecules is impeded as is the case at solid surfaces where there are boundary layers of liquid a few molecules thick. The tensile strength may also be calculated from Dupré's equation. One arrives again at equation (3) where σ now means the surface tension.

From this one can also calculate approximately the maximum force necessary for tearing.

Tensile strength, viscosity, atmospheric pressure, are factors which make up the "measuring block" effect (VIII). The facts mentioned above have to be taken into account when a body has to be brought from a state of rest to a state of motion (static friction) or in the presence of a few layers of lubricant molecules in sliding friction.[5]

The forces produced in thrust can be deduced from Newton's differential equation:

$$K = \eta \frac{dv}{dx} \qquad (4)$$

which only applies to laminar flow. The velocity gradient in a few layers of molecules is very steep even at low velocities. Hence, although the magnitude of the η which has to put into the equation is not known, large shear strains can occur which may be weakened by turbulences.

Another problem is the state of the adsorbed layers at the interface, i.e. whether this layer is predominantly liquid or solid in its properties. A definite solution has not been possible. Only let it be recalled that one boundary layer may be displaced by another one which is more active, so that one has to assume a certain mobility of the adsorbed layer as long as it is in contact with a liquid. If one considers the Dupré equation for the maximum work output again (see eq. (2)) then one notices that the work has to increase as σ_{ae} decreases. The maximum work which is also a measure of the wetting tendency is a maximum when $\sigma_{ae} = 0$ (miscible substances). From this it follows that when two points of lubrication (capable of alloying) are brought very close together a competition will ensue between lubricant molecules and surface atoms of the point of lubrication. The limited mobility of the atoms (molecules) of the solid is a decisive factor as is the displaceability and size of the lubricant molecules.[6]

If the lubricants contain substances of high chemical actifity so that they can directly react with the point of lubrication they will dissolve atoms out of the solid aggregate, thus forming new substances - mostly of an amorphous or highly viscous kind. The chemical effect is strongly dependent on temperature. The temperature observed at the point of lubrication does not matter because considerably higher temperatures may occur at the few possible points of contact or of proximity of the sliding planes. These higher temperatures may be equalized more quickly when the temperature of the bearing is low and the thermal conductivity of the bearing and of the lubricant is high. It depends on the velocity of reaction whether or not a temperature "flash" will have any effect. This also applies to the thermal and oxidative stability of a lubricating film in general. The consequences of chemical lubrication consist of corrosive planing down of the projecting microscopic and macroscopic irregularities and the admixture of the lubricating film with liquid or amorphous compounds. The abrasion which occurs, and which is a function of the lubricant may, as has already been mentioned, be caused in two ways. Either, the projections which may or may not be covered with lubricant may be broken out of the aggregate when they strike on one another, new hollows and therefore new projections being formed, or, atoms or particles may be torn out when high shearing and tensile stresses occur when two lubricating points slide past or jolt over each other. The smallest particles or atoms occurring during normal wear are extremely reactive and are probably already oxidised by the oxygen present in the air.

II. Machine for investigations in the non-hydrodynamic regions.

An instrument which is employed for the purpose of elucidating problems in lubrication from the point of view of friction must register very small changes in the friction of lubricants of practical interest, the readings being quickly and accurately reproducible at various temperatures. As the available instruments for various reasons did not offer any inducement to their being employed in an investigation of this kind, the instrument was built whose principle may be seen from the diagram in fig.1. In addition to the qualities mentioned it has the advantages of simplicity in construction, ease of manipulation, and of allowing the exchange of similar lubrication points. It consists of three balls fixed in one plane (the third ball not being visible in the figure); they form the guiding bearing. A fourth ball serves as sliding body. We are here dealing with a case of "three-point contact" (IX) which allows the use of high pressures per unit area and a good reproducibility of the points of contact, the degree of smoothness being high. With undamaged balls the distribution of pressure at the point of lubrication varies widely, being governed by the "Hertz flattening" and thus we have a state corresponding to a lubrication slit under practical conditions. The three lower balls are symmetrically arranged in a cup built into a thermostat. The fourth ball provided with a ventilator wheel, runs in the bearing formed by the three other balls. The ventilator wheel is milled with radial symmetry; any arbitrary load may be applied to it by means of weight-discs which are mounted centrally; it is driven by the air from two tangentially symmetrical nozzles. The air-jet may be regulated by means of a flow-meter or manometer so that corresponding to the resistance to be overcome by the wheel and the ball, the wheel can just be kept in uniform slow motion. The friction in the counter bearing may here be completely neglected. A nozzle (not represented in the drawing) through which air is blown manually by means of a rubber ball, is provided to set the wheel in motion. In general the actual measurement is so made that by altering the velocity of flow by 0.2 litres/min. the rotor, which until then has not been running uniformly, now runs with uniform speed. Prior to this adjustment in air-flow the rotor should stop after one slow revolution; and afterwards two or three complete revolutions should be timed. The necessary constant temperature is attained with a "Hoppler - ultra" - thermostat, type H.8.) A "Rotameter" 9.) is provided for measuring the flow of air, the range of the instrument is between 5 and 60 litres/min.

III. Experimental results

The force imparted to the sliding bodies from the ventilator wheel cannot be directly computed from the cross-section of the nozzle, the volume of air, etc. As the following experiments are carried out mainly for purposes of comparison, the effective force is not measured in units of force but given in terms of litres/min. of air. In order to be able, however, to determine the approximate value of the coefficients of friction, particularly the dependence of friction on the pressure, the effective force was measured roughly. Two thin threads were wound on the shaft of the rotor, for this purpose, and led horizontally over two pulleys in opposite directions parallel to each other. The threads end in two weighed aluminium discs which may be loaded with the necessary weights. The rotor will require a certain quantity of air per minute to be kept in uniform slow motion; therefore the air is throttled or opened step by step and the discs loaded until the rotor again executes uniform slow motion. The curve in fig.2 was obtained on consideration of the frictional resistance of the two pulleys as a function of the load.

the diameter of the running track of the running ball was taken to be 5,77 mm.[10] and the diameter of the axle of the rotor 6.05 mm (ratio of diameters 1:1.05). This was taken into account.

The normal force N, the resultant of the forces normal to the tangential planes of the points of contact (points of lubrication) of the balls has to be known before the coefficient of friction can be calculated.

$$P = 3\ N \sin\alpha = \frac{3\ N\ .\ r}{\frac{r}{2}\sqrt{6}} = \frac{6}{\sqrt{6}}\ N$$

$$N = \frac{P}{\sqrt{6}} = 0.4082\ P; \quad 3\ N = 1.225\ P$$

Thus, in order to obtain the sum of the load forcer one has to multiply the weight of the rotor by 1.225.

When the first tentative experiments were made on the effect of the viscosity (measured in the usual way) and the load, it was found that a highly viscous[11] hydrocarbon oil H 140 (H-oils of the I.G.) with 3863 cst at 20°C. gave the following values in coefficients of friction ($\mu = \frac{R}{P}$) for the same balls.

Weight of rotor in gm.	Resultant load in gm.	litres air/min.	μ
(50)[12]	61,2		0,103
(150)	180		0,100
250	306	26,0	0,101
500	612	36,3	0,106
750	920	42,7	0,104
1000	1225	48,2	0,105

A hydrocarbon oil of low viscosity, H16 with 324 cst. at 20°C. also needs 26.0 litres/min. with 250 gm. rotor weight applied to the same balls. An "active" synthetic oil of the DVL with 1970 cst gave the following values at 20°C.

Weight of rotor in gm.	litres air/min.	μ
250	20,1	0,060
500	28,3	0,061
750	35,1	0,066
1000	39,7	0,065

The measurements were exact to within ± 0.1 litre/min.[13] From this it may be seen that decreasing the viscosity by the factor 10 produces practically no change in the coefficient of friction in the example quoted. When the composition of the lubricant is altered the μ value is reduced from 0.101 to 0.060. Neither do the values seem to be dependent on the pressure. Abrasion, in the form of a running track (more visible by breathing on the cold ball) may be observed after the rotor has been running for only a very short time; abrasion may also be seen in the form of worn areas on the lower balls. The quoted examples show that the machine does actually operate in the required region. The accuracy and the resolving power of the instrument are high; thus, for the present it seems suitable for an investigation into the region of lubrication that is of interest here.

The following questions or effects have to be investigated with the aid of examples before any relationships can be found by measurements using very varied substances.

1.) Cleaning of the points of lubrication.
2.) Uniformity of the surfaces of the balls.
3.) Change in the geometrical form of the points of lubrication during the test (wear).
4.) Strength of the lubricating film.
5.) Effect of surrounding atmosphere.
6.) Change in the surface structure of the point of lubrication due to the lubricant.
7.) Nature of sliding of the rotor.
8.) Surface roughness of the working material. In addition there are the effects about which direct information is wanted.
9.) Lubricant.
10.) Load.
11.) Temperature.
12.) Working substance.

In the present paper preliminary answers are given to these questions, thus paving the way for later more thorough and systematic investigations.

1.) Cleaning of the points of lubrication.

The ball-bearings obtainable from the industry[14] are greasy and contain mechanical impurities such as dust, etc. They are carefully wiped with a cloth moistened in alcohol-ether, then placed in the cup together with the clamp ring and the gripping nut of the rotor; the clamp ring screw is just tightened so far that the ring does not fall off; a small funnel, whose sharp edges have been rounded off in the flame is then placed on the bottom of the cup; the latter is then fixed by means of a wire-loop below a reflux condenser ground to fit a flask with a long and wide neck. The extraction proceeds with rapid reflux with a mixture of 2 parts ether and 1 part methyl alcohol. A few granules of potassium hydroxide are put into the boiling flask so as to neutralise any acid components of the lubricant. In this way the balls clamped in the cup are also cleaned without their position being altered. The rotor-ball must, after some superficial cleaning, be dipped into a fresh ether-alcohol mixture and rinsed for some time with a dropping bottle. The parts which have been treated in this way are warmed in the drying oven for 5 mins. at 50°C. and while still warm are dried in the vacuum desiccator (without $CaCl_2$) by evacuating and allowing in air three times.

Friction without application of lubricant at at 20°C: Method of measurement: Only during 1/3 of one revolution does the rotor ball (6.05mm.) have a free course. The measurement is therefore not carried out in the usual way. The ventilator wheel is turned by hand over very short distances and it is observed whether there is any tendency for a continuation of the movement. The values obtained in the experiments without lubricant can be measured accurately to within about ± 1 litre per min. The reproducibility is bad. See 4 (Plate 17.18) regarding the connection of the normal measurements with the ones obtained in the way described here.

The experiments were carried out at 20°C. in a nitrogen atmosphere with a rotor weight of 250 gm. Cleaning for 10 mins. gave results similar to those obtained after 20 mins. cleaning, viz. about 43 litres/min. (0.3μ) over the first third of the path. Up to the third third of the path the value rises to about 46 litres/min. (0.4μ), within 2 or 3 revolutions it then rises to above 60 litres/min. (0.7μ). Other measurements gave 50 litres/min. (0.45μ) even for the first third of the path.

In as far as there is no plastic deformation a periodic elastic flattening and reformation of the sliding ball surface thus occurs at the lubricating point during the motion of the rotor under conditions of optimum bevelling.18) The sliding surface of the sliding ball is about 250 times as large as that of the fixed balls; this has to be taken into account in the wear. In a normal determination the sliding velocity is about 5 mm/sec.

The variation of the visible signs of wear (100 fold magnification) with the number of revolutions of the rotor may be seen from the following examples: weight of rotor 250 gm. 20°C, air, balls wetted:

Revolutions of rotor, about	Lubricant	litre/min.	Visible signs of wear.
10	423/40 hydrocarbon oil 892 cst	25.3	Very faint uniform grooves having an elliptical boundary Ø : 0.08; 0.09 mm.
10	Speedwell 1044 cst	23.5	Well-marked grooves, having an elliptical boundary distorted almost to rectangle Ø : 0.08; 0.09 mm.
100	423/40	25.7 after 100 revs. 25.5	Uniform grooves having a nearly elliptical boundary: Ø : 0.08; 0.09 mm. with more deeply marked circular (Ø : 0.06 mm) area of wear, coloured light brown, in the middle.
100	Speedwell	22.7 after 100 revs. 23.7	Uniform grooves, somewhat more accentuated than in 423/40 Ø : 0.08; 0.09 mm.
100	Synthetic oil SS IV DVL (1970 cst)	19.3 after 100 revs. 19.3	Very uniform very faint grooves, having an elliptical boundary. Ø : 0.08; 0.085 mm.
600	423/40	25.9 after 600 revs. 25.1	Very few grooves with a sharp elliptical boundary. Ø : 0.08; 0.095 mm.
600	Speedwell	23.5 after 600 revs. 23.7	Uniform well-marked grooves with a sharp (jagged) elliptical boundary. Ø : 0.095; 0.10 mm.

Revolutions of rotor, about	Lubricant	litre/min.	Visible signs of wear.
600	H 16 324 cst	25.3 after 600 revs. 25 ± 0.3	Faint grooves with an elliptical boundary. Ø : 0.12; 0.14 mm.
600	none	60	Ø : 0.28; 0.30 mm.

In contrast to the preceeding experiments, the point of lubrication had a concave appearance in the last four experiments. The track of the running ball in the three last experiments is directly visible, in the preceeding experiments only after breathing on it.

The diameter of the worn areas of the stationary ball is larger than the calculated Hertz flattening, even after only a few revolutions of the rotor; this is due mainly to the roughness of the ball surfaces apart from the inexactness in the calculation. The diameter of the worn areas increases appreciably only after the concave shape has been produced, so that the distribution of pressure over the area of lubrication changes steadily up to 600 revs. (run of 30 mins.) for a more or less constant average load, without any appreciable change in the coefficient of friction. The amount of abrasion for the thin H 16 is distinctly greater than for the preceding oils although there is no difference in the values of the friction.

Since the amount of data available at the present time is small, particularly as regards lubricants of very low molecular weight, it is still too early to enter more fully into the matters just mentioned.19.)

4.) Strength of the lubricating film.

The determinations were carried out with a full cup and with the balls well wetted. In this way the properties of thin films were observed.

Experimental values which have been obtained with full cups have been related below to the results obtained with the balls wetted (about 3 drops of lubricant). Weight of rotor, 250 gm, 20°C, air.

Lubricant	Viscosity cst.(20°C)	Full cup litre/min.	Balls wetted litre/min.	Difference litre/min.
423/40	892	25.5	25.5	0
Speedwell	1044	23.1	22.9	- 0.2
SS IV DVL	1970	20.4	19.7	- 0.7
H 140	3863	25.9	25.3	- 0.6
H 16	324	25.2	25.3	+ 0.1

The higher values of the friction with the full cup are probably due to the viscosity and possibly to thixotrophy (at the boundary faces) since a deficiency of lubricant in the case of the well wetted balls is not to be anticipated to any greater extent than when the cup is full in the case of measurements carried out in so short a time.

In order to produce very thin films of varying strengths the following two methods were used:

a.) Dipping in dilute solutions.

Solutions of lubricants in benzene were poured on to the balls in the cup and centrifuged off again after a definite time (3 min.) and then dried as usual. The clamped rotor ball was treated similarly. The measurement was carried out as indicated on page 7 (for a third of the path). The rotor was not however set in motion by touching it with the hand but by vibrations set up in the instrument by impulses. The accuracy in this case is about ±0.5 litres/min, the reproducibility which depends on the kind of impulse and the shaking off of the solution is ± 1 litre/min., weight of the rotor 250 gm., 20°C, nitrogen (except in experiments 3, 4, 9).

Lubricant film from 0.25% solution

Number of revolutions	1/3	2/3	3/3	2	8	10	14	20	30	100
litre/min for 423/40	28.5	28.5	28.5	28.5	27.3$^{20.)}$		29.5	29.5		26.3$^{20.)}$
litre/min for Speedwell	25.5	25.5	25.5	25.5	26.5	29.5	36.5	39.5	45.5	

Measured in air (experiment 3.4)

Number of revolutions	1/3	2/3	3/3	2	8	10	14	20	80	100
litre/min for 423/40	27.5	27.5	27.5	27.5	26.1$^{20.)}$		27.5	27.5	25.5$^{20.)}$	27.5
litre/min for Speedwell	25.5	25.5	25.5	26.5	28.5	30.5	33.5	46.5		

Lubricant film from 0.10% solution

Number of revolutions	1/3	2/3	3/3	8	10	25	35	40	45	50
litre/min for 423/40	29	29	29	28.5	28.5	29.5	32.5	36.5	44	>50
litre/min for Speedwell	25.5	26.5	27.5	41.5	>50					

Lubricant film from 0.05% solution

Number of revolutions	1/3	2/3	3/3	2	4	8	14	20	30
litre/min for 423/40	28.5	29.5	29.5	29.5	28.5	29.5	30.5	34.5	>52
litre/min for Speedwell	26.5		30.5	31.5	35	>50			

Measured in air (experiment 9)

Number of revolutions	1/3	2/3	3/3	2	4	8	14
litre/min for 423/40	29.5	29.5	29.5	29.5	31.5	40.5	>52

Lubricant film from 0.01% solution.

Number of revolutions	1/3	2/3	3/3	1.5
litre/min for 423/40	34!	39.5	42.5	>50
litre/min for Speedwell	35!	39	43.5	>50

Under 100 fold-magnification the lubrication film on the rotor ball is still visible when it is made from a 0.05%.sd.[21] The effect of the time for which the balls are in contact with the lubricant solution was also investigated in a particular case; no appreciable effect was found. In the measurements with thin films the rotor is more easily set in motion in the case of compounded oils than in the case of mineral oil and more easily than with normal wetting. (decrease in "static friction") (extensive orientation of molecules).

It is seen that thin films are quickly used up or destroyed and that for compounded oils this occurs quicker than it does for hydrocarbon oil.[22] Causes of this might be different oil-consumptions due to different types of abrasion, differences in the rate with which more lubricant is supplied to the lubrication point, and temperature stability - these questions are still being investigated in detail.[23]

The following values were obtained with the normal methods of measurement; weight of rotor 250 gm; 20°C; nitrogen.

Number of revolutions	3-5	15	50	80
litre/min for 423/40 from a 0.3% sol.	27	28	28	28

Calibration value of balls with 423/40: 26.7 litres/min.

Number of revolutions	3-5	15	50	80	
litre/min for 423/40 from 0.15% sol.	25.7	increasing rapidly			
litre/min for Speedwell from a 0.4% sol.	23.3	25.2	27	32	increasing rapidly

Calibration value of balls with Speedwell, 22.9 litres/min.

Number of revolutions	1/3	2/3	3/3	2-5
litre/min for Speedwell from 0.05% sol. and wetted with 423/40	method of measurement as on P.7. 26.5	26.5	26.5	normal method of measurement 25.5!!
	(re-calibration of balls with 423/40; 25.7 litres/min)			
litre/min for 423/40 from 0.05% sol. and wetted with Speedwell				24.6!!

b.) Immersion of the balls in lubricant and centrifuging.

The centrifuging was done for 3 hours at 3500 revs/min. After centrifuging the balls exhibit a surface glittering with colour. The oil film is still so thick that the tracks produced by a needle flow together again slowly. The results show the same tendencies as those with films produced from solution. 24.) The running track is rather dry in the case of Speedwell and it is covered with brown grindings; with 423/40 on the other hand the running track shows no appreciable grindings and is wetted with oil.

The centrifugal method should be particularly suitable for testing ball-bearing greases.

5.) Effect of the atmosphere.

The effect of oxygen of the air on very thin lubricating films was now shown; in the presence of air the films were destroyed somewhat more rapidly than in a nitrogen atmosphere. Tests were also made on the effect of various gases; the same balls were always wetted with 423/40; they were left for 15 mins each in an atmosphere of nitrogen, oxygen, and carbon dioxide respectively and then rated in the machine. The only difference was observed in the case of carbon dioxide (decrease of the friction value by 0.2 litres/min.) but even then only within the limits of experimental error.

6.) Change in the surface structure of the area of lubrication due to the lubricant.

Visible wear (under 100 fold magnification) occurs, as has already been shown, as soon as the rotor starts running, the type of wear being dependent on the lubricant used; evidence of this is to be observed on the worn areas of the three fixed balls. A compounded oil of average friction values shows deep grooves whereas a hydrocarbon oil of higher and a synthetic oil of lower friction value both yield uniform, relatively smooth abrasion areas. These visible differences in the surface as well as the differences in the grindings and the oil reaction products which are not visible may affect the friction decisively; this may be seen from the following tests carried out under identical conditions.

The oils 83/43 and 52/44 were measured in various sequences (a special run-in was avoided) in as short a time as possible (3 to 5 revolutions). For each sequence the same set of clamped balls was used; weight of rotor 250 gm; 20°C; air; balls wetted.

Lubricant	83/43	52/44	83/43	83/43	52/44
litres/min.	24.9	24.7	23.9	23.9	24.6
litres/min.	25.1	24.9	24.1		

Lubricant	83/43	H 426	83/43 25.)	
litres/min.	25.1	26.5	26.2	
		27.9	25.1	after 2½ minutes running-in. 26.)

No change was produced here when the points of lubrication were wiped with cotton cloth before the usual cleaning was started.

Other oils - also those with very active groups, such as SS IV DVL - do not show the properties exhibited by the oils above.

Lubricant	83/43	SS IV DVL	83/43
litres/min.	26.1	20.3	26.1

Running-in properties of a highly compounded oil (Speedwell):

Running-in time in mins. 26.)		1	2	3	4	5
litres/min.	22.7	23.4	23.3	23.7	23.7	23.7
litres/min.	23.5	23.9	23.9	24.3	24.1	23.5
litres/min.	23.3	23.5	23.9	24.3	24.9	25.1

The values thus have a very low degree of reproductibility.

H 426 (Ester) for example has better characteristics in this respect.

Running-in time in mins.		1	2	3
litres/min.	26.5	28.1	27.9	27.9
litres/min.	26.4	28.1	27.9	

The hydrocarbon oil 423/40

Running-in time in mins.		1	2	3	4	5
litres/min.	26.1	26.1	26.1	26.1	25.9	25.9
litres/min.	25.7	25.3	25.5	25.5	25.5	25.5
litres/min.	25.9	25.7	26.0	26.0	26.0	26.0
litres/min.	25.3	25.3	25.3	25.3	25.3	25.3

The lubricant SS IV DVL

Running-in time in mins.		1	2	3	4	5
litres/min.	20.3	20.3	20.3	20.3	20.3	20.3

From the second and third row of the table of running-in characteristics of 423/40, it is evident that initial irregularities in the surface had been removed in the running-in process.

It was shown in one case that the reproducibility of the running-in characteristics is low for many lubricants. The causes of this are probably the same that were mentioned in explanation of the increase in the friction values for very thin films, viz. non-reproduceable factors.

Those oils which do not appreciably affect the area of lubrication should therefore be chosen as calibration oils. These oils should also be run in for a short time so as to even out any irregularities in the surface of the balls (maximum time for running-in, 1-2 mins, if any variations are observed while the calibration value is being determined; see above example with 423/40.)

Another example is given which shows good reproducibility for running-in characteristics and for the preparation of running-in track. The values which have been quoted here are the maximum values obtained during the running-in. (Time of running-in: 30 secs. to 1 min.)

Lubricant	litres/min.	Lubricant	litres/min.
83/43	25.1 (calibration value)	H 8	26.3 (calibration value)
H 426	28.1	H 426	28.3
	3.0 difference		2.0 difference

83/43	25.3 (calibration value)
H 8	26.3
	1.0 difference

The difference of 3.0 corresponds to the sum of the differences of 2.0 and 1.0.

7.) Type of sliding of the rotor.

During more rapid movement, particularly on thin and very thin oils, the rotor very easily assumes a motion which is accompanied by a singing noise (X); the values obtained in this state are considerably lower than those obtained in true sliding. This kind of movement was avoided in all the determinations, e.g. in dry runs the rotor was allowed to slide very slowly over short lengths of its path, thus foregoing some accuracy. These determinations have been specially marked in the present report because they cannot be compared directly with the normal measurements.

8.) Surface roughness of the working substance.

The roughness of the surfaces was produced by etching the balls with hydrochloric acid.

Etching (of the cleaned balls) 3 mins. with 25" HCl; weight of rotor 250 gm; 20°C.; air; balls wetted:

Lubricant	litres/min.	μ	(μ for smooth balls about)
423/40	29.7	0.137 (calibration value)	(0.101)
SS IV DVL	27.0	0.110	(0.060)
		0.027 difference	0.041 difference

Running-in characteristics of SS IV DVL:

Running-in time in mins.	1	2	3	5	7
litres/min.	27.2	27.2	27.2	26.8	26.2 (levelling up)

Etching: 5 mins. with 25% HCl; weight of rotor 250 gm; 20°C; air; balls wetted:

Lubricant	423/40	Speedwell	423/40
litres/min	29.9	27.5	29.9
litres/min	30.0	27.5	29.9

after running-in for 1 min.

Experiments are planned with deeply etched and with sand-blasted balls. In one experiment with sand-blasted balls (wt. of rotor, 250 gm; 20°C.) and 423/40 (calibration oil) a friction value of 30.3 litres/min. was obtained; with Speedwell it was 28.1 litres/min.

The resolving power of smooth balls is greater than that of rough balls.

9.) Influence of the lubricant.

Here the main task is to determine the resolving power of the machine and also the characteristics of the lubrication region in which it works. No relations were therefore sought for the present between coefficients of friction, the composition of the lubricant and the physical properties, with the exception of the viscosity. All the determinations were carried out with 250 gm. rotor weight at 20°C. in the presence of air and with wetted balls. Oils having greater viscosities than the ones mentioned above were not available; only few measurements have on the other hand been made with oils of low viscosity (below 100 cst at 20°C.) so that insufficient experience has been gained in this region; the few values which have been obtained are therefore reported with some reservations.

In the table below the viscosities of various lubricants (150 - 4000 cst) are related to their running-in characteristics.

Lubricant (Hydrocarbon base)	H 8	H 16	H 32	H 88	H 140	83/43	423/40	133/43	224/38
cst at 20°C.	145	324	759	2355	3863	898	892	730	1281
calibration value with 423/40 litres/min.	25.3	24.9	25.3	25.7	25.3	25.3	25.3	24.9	24.9
litres/min. after running-in time in min.[27]	26.3	25.1	25.3	25.3	25.1	25.3	25.3	24.0	24.2
1	26.3	25.3	25.1	25.3	25.1	25.3	25.3		24.1
2		25.3	25.1	25.3	25.1	25.3	25.3		24.1
3		25.7	25.1	25.3	25.1	25.3	25.3		24.3
5		25.7	25.3	25.3	25.1	25.5	25.3		

Lubricant active subst.	H 426	Speedwell	Kompr. 183/39	SS IV DVL	Ab. 30 Ester	ASM 18/39	Hypoid 358/42	HDL 357/42
cst. at 20°C.	137	1044	1096	1970	3600	1104	927	942
Calibration value with 423/40, litres/min.	25.1	25.1	26.1	26.1	25.8	25.3	25.3	25.1
litres/min. after running-in time, in mins.	26.5	22.3	25.1	20.3	27.2	26.0	25.3	25.1
1	28.1	22.9	25.1	20.3	27.2		25.1	25.1
2	27.9	23.5	25.1	20.3	27.2		25.1	25.1
3	27.9		25.5	20.3	27.2		25.1	25.1
5			25.5	20.3	27.0	26.3	25.1	25.1

Table of friction values determined from the above data without running-in:

Lubricant Hydrocarbon base.	H 8	H 16	H 32	H 88	H 140	83/43 28.)	133/43 28.)	224/38
cst at 20°C.	145	324	759	2355	3863	898	730	1281
μ 29.)	0.110	0.103	0.101	0.098	0.100	0.101	0.094	0.095

Lubricant active subst.	H 426	Speedwell	Kompr. 183/43	SS IV DVL	Ab. Ester 30.)	ASM 18/39	Hypoid 358/42	HDL 357/42
cst at 20°C.	137	1044	1096	1970	3600	1104	927	942
μ	0.114	0.079	0.094	0.060	0.114	0.106	0.101	0.101
μ (max. value after running-in)	0.129	0.09						

Coefficients of friction of some substances of low viscosity (working with a full cup)

Lubricant.	Spindle oil 160/38	Perhydrochrysene	Refrigerator oil 159a/38	Bone oil	Cetane	Cetene	Ethyl Alcohol
cst at 20°C.	142	85.7	30.8	30.2	4.47	4.45	1.52
μ	0.127	0.137	0.125	~0.17	~0.46!	0.125!	0.7

It should be mentioned that some oils, when left on the balls for a few days, show drops in the friction values varying from 0.2 to 0.6 litre/min. 31.) Reactive additives have little effect at 20°C. Thus a hydrocarbon oil (93/43) with 26.1 litre/min. only showed a fall in the friction value down to 25.4 litre/min. after 2% SS IV DVL had been added. When 2% of oleic acid was added to the same oil the reduction in the friction value amounted to 0.4 litres/min.

The accuracy of the determinations was ± 0.1 litres/min. The reproducibility of the values in the above tables obtained without running-in was ± 0.1 litres/min. (when regard was had to the points mentioned). When lubricants show marked and immediate running-in deviations the reproducibility cannot easily be made so high.

From the examples it can be seen that:

Within certain limits the viscosity at 20°C. measured under normal conditions, does not affect the friction. Where these limits are overstepped friction rises somewhat, it approaches the values for dry friction with substances of very low molecular weight. The conventional "activity" of an oil is in no way a measure of the friction characteristics. One has to pay final attention to friction on a previously used sliding surface and on one which has already been run-in.

10.) Effect of load.

Two examples illustrating the effect of load have already been given at the beginning. The following ones are added:

Lubricant	load gm.	litres/min.	μ
H 16	250	25.1	0.097
	500	35.1	0.099
	1000	47.8	0.103
133/43	140	19.7	0.100
	250	25.7	0.100
	500	36.1	0.104
	1000	48.5	0.107
SS IV DVL	50	9.	0.055
	100	14.1	0.055
	200	19.5	0.054
	250	21.7	0.055

It is seen that the coefficients of friction increase slightly with the load, which confirms the results of the previous experiments. It cannot be said quite definitely whether this increase is genuine, for it has already been mentioned that the actual effective force cannot be measured as accurately as the relative force in litres/min. (Here one has to have regard to the increased plastic and elastic deformation of the balls under higher loads.)

11.) Effect of Temperature.

It is regretted that the effect of temperature which is one of the most important questions could not yet be investigated to the desired extent.[32]

The coefficients of friction of various lubricants at 20°C. have been shown on page 17. From the following it will be seen that the relative magnitudes of these may already have changed at 80°C. Weight of rotor 50 gm; 80°C; nitrogen; balls wetted.

Lubricant	423/40	Hypoid 358/42	H 140	H 32	Compressol 183/39	Speedwell
cst at 80°C.	36.5	30.0	112	40.05	38.0	60.0
Calibration value with 423/40 litres/min.	14.1	14.7	14.1	14.3	14.5	13.9!
litres/min. after running-in time in mins.	14.1	14.5	13.9	14.9	13.9	13.9!
1	14.3	14.1	13.9	14.5	13.7	13.9
2	14.1	14.1	13.9	14.5	13.7	13.9
3	14.1	14.1	13.9	14.5	13.5	13.9
5	14.0	14.1	13.9	14.5	13.7	13.9

Weight of rotor 38 gm. 80°C. air; balls wetted.

Lubricant	ASM	ASM	SS IV DVL	SS IV DVL
Calibration value with 83/43 litres/min.	11.6	11.5	12.5	12.5
litres/min.	10.9	10.7	11.7	11.6

At 20°C. the ASM value is 0.2 - 0.4 litres/min. higher than the value of 83/43; at 80°C. it is lower by 0.7 - 0.8 litres/min.

The examples below give the friction values of some oils at various temperatures. (Weight of rotor 38 gm; air; balls wetted; vertical slits; same balls.)

Lubricant	83/43	83/43	ASM 99b/42	133/43	SS IV DVL	SS IV DVL
litres/min at °C.						
80	11.8	11.1	10.5	11.4		10.6
60					9.3	
40					8.1	
20	9.6	8.9	9.1	10.2	7.3	7.5

The reproducibility has been measured with lubricant 83/43 at 80°C. using the same (clamped) balls throughout (the balls were cleaned after each observation. Weight of rotor 50 gm; air; balls wetted: 14.3; 14.3; 14.3; 14.2; 14.3 litres/min.

At high temperatures (100 to 200°C.) the results are also affected by the change in the lubricant. The behaviour was therefore tested both in a nitrogen atmosphere and in air. No values have been given since the number of experiments, which in addition were only make-shift, was too small to allow of a judgment on the reproducibility. It would seem that friction was greatest between 80°C. and 120°C. and that it falls off again at higher temperatures. The values are dependent on whether the temperature was raised slowly (marking out of specific sliding paths) or whether the measurements were directly made at the required temperature.

13.) Effect of the working substance.

The observations were made with balls which had been electrolyticall coated with various metals. No results are available at present.

IV. SUMMARY AND CONCLUSIONS.

First non-hydrodynamic lubrication is defined and its theoretical principles are presented briefly. An instrument is then described with smooth points of lubrication which has a convenient method of measurement and a simple construction (four-ball ventilator wheel machine). For lubricants with viscosities of from 300 to 4000 cst that have been tested so far, the machine gave coefficients of friction between 0.060 and 0.120 (at 20°C.) independent of the viscosity at 20°C. measured under normal conditions. A variation of the average load on the points of lubrication between 3000 and 8000 kg/cm^2 has only a small effect on the coefficient of friction. These properties therefore correspond to"boundary friction" by definition. The change in the distribution of the load on the Hertz plane occurring during the running-in (wear) also has practically no influence; neither has the change in the specific load caused by the ensuing enlargement of the area of lubrication. The lower range of viscosities - roughly explored down to 5 cst - shows coefficients of friction which are only slightly higher; with substances of very low molecular weight, on the other hand, the conditions resemble those in dry friction. According to the experience gained so far the accuracy of the observations on substances which have a coefficient of friction about 0.11 is ± 0.001 (± 0.1 litres/min.) and it becomes ± 0.001 to ± 0.002 (± 0.1 to 0.2 litres/min) when μ is about 0.15. In general the reproducibility corresponds to the above figures where due regard is given to the factors discussed in the report.

The following tentative conclusions on the lubrication processes occurring in the region of boundary lubrication can be directly drawn from the preliminary experiments.

Lubricants - including those manufactured by similar methods - show significant differences in the coefficients of friction under selected conditions. The presence of "active" (polar) groups does not give a direct indication of good or bad frictional characteristics.

At higher temperatures the relative friction values of lubricants may change or may even be inverted.

Their lubricant films (visible under the microscope) which have been applied at the point of lubrication and which give the same coefficient of friction as does excess of lubricant have a very low life. The life is greater for hydrocarbons than it is for the "active" substances having lower coefficients of friction which have so far been tested. Still thinner films immediately give higher friction values (here the conditions of the supply of lubricant from the surroundings of the sliding path and within it, and the conditions of abrasion, etc. have to be taken into account.)

The friction behaviour can be observed not only on the prepared sliding surface but also on the sliding path produced during the running-in under the action of the lubricant (variation in the work done during wear/cm^2).

Thin lubricants (about 5 cst at 20°C.) seem to have coefficients of friction at 20°C. which are similar to but somewhat hither than those of the lubricants which have been tested thoroughly (300 to 4000 cst at 20°C.). Very thin substances, however, have friction values which approach those measured in dry friction.

Small proportions of additives generally have only a small effect on the friction at 20°C. even when they are adsorbed by the boundary faces of the area of lubrication. This is because they are used up more quickly than they are supplied and because the structure of the carrying film is apparently disturbed.

On the basis of this preliminary explanation of the factors controlling lubrication the following are now investigated in detail: Lubricants of the most varied viscosities and kind in order to find a connection between friction and wear; this is based on the one hand on the capacity of various lubricants for keeping two surfaces separated in the boundary region (size of molecule, intermolecular forces in the lubricating film on the boundary surface, etc.) and on the other hand on the work done in the wearing process per cm^2 (directly and indirectly) as a function of various oils, the two factors being considered as separate entities but as acting simultaneously.[33] Then, the dependence of these factors on the chemical and physical properties of the lubricants and working substances of the points of lubrication. Then temperature characteristics and the properties of very thin lubricating films. The general considerations brought up in the introduction are used as working hyoptheses and an attempt is made to provide evidence for them.

Name of Oil	Entry No.	Sp.gr. at 20°C.	Viscosity in cst at °C.		m	VP
			20	50		
H 8	248/43	0.841	145.5	34.4	3.42	1.51
H 16	249/43	0.851	324	67.2	3.18	1.52
H 32	250/43	0.853	759	130.3	3.13	1.62
H 88	251/43	0.854	2355	318.7	2.98	1.66
H 140	252/43	0.861	3863	476.7	3.00	1.74
H 426	253/43	0.948	137.5	28.2	3.80	2.08
Gunring	224/38	0.885	1281	177.6	3.21	1.74
Rotring	83/43	0.889	898	133.8	3.44	2.02
Rotring	133/43	0.874	815	127.6	3.32	1.83
Rotring	423/40	0.892	892	130.6	3.36	1.89
Speedwell	-	0.960	1044	195	2.82	1.41
Kompressol	183/39	0.959	1096	143.5	3.48	2.10
ASM	18/39	0.917	1104	160.1	3.29	1.87
ASM	99b/42	0.922	1051	147.2	3.42	2.00
Hypoid oil	358/42	0.927	927	116.3	3.70	2.41
HDL	357/42	0.932	942	116.3	3.74	2.50
Compressor oil	52/44	0.912	828	111.7	3.62	2.24
SS IV DVL - Synthetic oil	-	0.942	1970	177.5	3.94	3.13
Abietic Acid Methyl Ester	-	1.038	7349	201.4		
Russian Spindle Oil	160/38	0.898	142	22.7		
Refrigerator Oil	159a/38	0.886	30.8	9.1		
Perhydrochrysene	-	0.984	85.7	16.2		
Bone Oil	Shell P 31	0.860	30.2	9.08		
Cetane	-	0.770	4.47	2.36		
Cetene	-	0.793	4.55	2.39		
Ethylalcohol	-	0.789	1.52	0.89		

The viscosities of the H oils refer to the data given by the I.G. and were not verified since any change would be irrelevant in the present work. Moreover the H oils, apparently because of ageing, give saponification numbers. It is intended to carry out experiments with highly purified oils.

FOOTNOTES.

(I) A.V.Philipovich,"Delimitation of conceptions frequently used in lubrication." Journal of the VDI, vol.86, p.408 (1942).

1.) The expression "partial lubrication" would be more fittingly applied to genuine partial lubrication, i.e. wherever dry friction also occurs.

2.) It is shown later that hydrodynamic effects are not found in practice in lubricants with viscosities between 150 and 4000 cst at 20°C.

(II) Dupré, "Théorie mécanique de la chaleur", Paris, 1869.

3.) Here it would be assumed that the particles become disengaged simultaneously from the point of lubrication with the wetting by the lubricant; this seems not unreasonable.

(III) W.v.Engelhardt, Nachrichten der Akademie der Wissenschaften, Göttingen, 1942, number 2.

4.) See however, also p. 7 in original. etc.

(IV) Remark by the author in the discussion on the paper by W.V.Engelhardt in KWI of 14.7.1943.

(V) See also Budgett, Proc.Roy. Soc. A 86, 25, 1911.

(VI) K.L.Wolf has recently represented the terms adhesive strength (force = work/path) and viscosity as the main factors in lubrication. Öl und Kohle 39, 404 (1943)

(VII) J. Meyer, Abhandlungen der Deutschen Bunsengesellschaft No.6, 1911. K.L.Wolf, Chemie 55, 295 (1942).

(VIII) See plate machine by Heidebroek and Pietsch. Forschungs-Ingenieur Wesen, vol.12. No.2, p.74/87.

5.) When there is a monomolecular layer between two similar solid surfaces one has to realise that this layer will adhere to both boundary faces - with equal strength even in the case of a symmetrical hydrocarbon. From this it follows that there will be work done on deformation corresponding to any shearing stress.(for work done on deformation see e.g. Holm: "Die technische Physik der elektrischen Kontakte.")

6.) One has to realize that on atomically plane surfaces a mechanical flowing off of a monomolecular wetting film is no longer possible even if the adhesion of the film were very small. (In structure this film is comparable to a layer of balls between two surfaces.) As a contrast we have the chaotic surface of an actual point of lubrication. Here the molecular layer may easily be imagined being pushed away or accumulated with a minimum of work expenditure, even with a gain of work. (see eq. 2)

The space required by the lubricant molecules or surface molecules should be mentioned in this connection. Starting with Gibb's equation (and assuming the validity of van't Hoff's law in this connection) the space required by liquids can be approximately calculated (Langmuir, J.Amer.Chem.Soc.39, 1883 (1917). Seelich, Zt. physik.Chemie 7.), or it may be determined with the Langmuir trough. These results, which by themselves are based on assumptions can however hardly be applied to solid (metallic) surfaces.

7.) Will appear shortly.

(IX) G.D.Boerlage (four-ball testing) Engineering 136, 46, (1933)
144, 1, (1937)

8.) Haake Bros, Medingen near Dresden.

9.) Rota instruments and machine manufacturers Dr.Hennig K.G., Aachen.

10.) Calculated without taking the Hertz flattening into account, the measurements were 5.8; 5.9.

11.) If not specially mentioned the viscosity is always given for a temperature of 20°C. The data were given in cst since this is the unit commonly employed in lubrication engineering; the values may be transformed to cP by means of a table given at the end of the report.

12.) Measured with a particularly light rotor and the values at 250 gm. (50 g. trans.note) taken as equal to those obtained with the heavy rotor of 250 gm.

13.) The reproducibility remains the same for a given load; for a changing load it amounts to about ± 0.2 litres/min.

14.) Vereinigte Kugellagerfabriken A.-G., Schweinfurt.

15.) It is shown later that the surface of the balls is visibly destroyed after only the first few revolutions of the rotor.

16.) In later descriptions of the experimental conditions, the atmosphere during the experiment is simply called "air", "nitrogen" etc. given in conjunction with the corresponding exp.-temp. Similarly, instead of "balls well wetted with oil" we simply put "balls wetted" and in the other cases write "cup full".

17.) The diameter of the balls should be constant to within ± 0.0005 mm.

18.) For a rotor weight of 250 gm. (d = 0.05 mm.)

19.) For general considerations see p. 3 bottom, 4, 7 top. (in original)

20.) Normal measurement, less accurate on account of the preceeding type of measurement, corresponds roughly to the value obtained with normally wetted balls.

21.) Judging from the appearance of the oil films on the balls (when the envelope of oil is scratched) under a 100 fold magnification it seems that the thickness of the film is fairly independent of the type of oil dissolved in the benzene. It is intended to make quantitative measurements of the thickness of films.

22.) The sudden change in the quantity of grindings when the load is increased for Kompressol in a certain region or for long runs, as found by C.F.Krienke, probably has the same causes. See C.F.Krienke, Abrasion measurements .. with various types of oil on the four-ball machine; Öl und Kohle, to be published shortly.

23.) Particularly the actual quantity of lubricant in the micro sliding surfaces of the two points of lubrication and in the hollows lying in between - storage cavities for the oil. (Change in the smoothness of the balls for lubricant films of various strengths).

24.) 423/40 showed no increase of the friction value after 300 revolutions of the 250 gm. rotor (26.1 litres/min. after 300 revs. 26.0 litres/min.). Speedwell on the other hand, starting with 23.5 litres/min. showed 50 litres/min. after 300 revs.

25.) 83/43 itself shows only little change during the running-in (the value rises from 25.3 to 25.5 after 60 revolutions).

26.) One minute corresponds to about 15 to 20 revolutions. By running-in or running-in characteristics we always understand the formation of a sliding-path characteristic of the lubricant and characterised by its frictional properties.

(X) Bowden, with his apparatus observed a stick-slipping. see e.g. F. Morgan, M. Muskat, D.M.Reed; Studies in Lubrication; J appl.Physics, 12, 743 (1941)

27.) A running time of 1 min. always corresponds to about 15 to 20 revolutions.

28.) Both are engine oils with the same (trade) mark and have been supplied one after the other. (83/43 sometimes leads to damage in the engine, 133/43 does not with the same engine.

29.) All the coefficients of friction in this report are referred to a ball-calibration value of 26.0 litres/min. for 423/40.

30.) Methyl ester of abietic acid; measured at 25°C. so that the viscosity becomes comparable with that of other oils.

31.) This cannot be a case of ordinary orientation of molecules because the lubricating film at the points of lubrication is used up as soon as the rotor starts moving whereas the lower value remains for some time. (Penetration of the lubricant into the surface of the slip-way?)

32.) The required high-temperature-thermostat from the firm of Haake was not supplied so that it was possible to make only a few make-shift measurements at higher temperatures.

33.) Under the same conditions lower work of abrasion/cm^2 gives more abrasion. Good lubricating properties: low work of abrasion per cm^2 but high carrying capacity of the lubricant in the boundary region.